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ANNUAL PROGRESS REPORT ON

STUDY OF MAGNETIC DAMPING EFFECT ON CONVECTION AND SOLIDIFICATION UNDER G-JITTER CONDITIONS

(for the period of June 1, 1996 - April 1, 1997)

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This report discusses the progress made during the first year of the NASA grant (NASA Grant #: NCC8-92) on the study of magnetic damping effect on convection and solidification under g-jitter conditions. The work entails both theoretical and experimental analyses of g-jitter driven flow in microgravity and the effects of magnetic field on the damping of g-jitter driven flows during solidification processing of conducting materials.

The goal of the first year is to develop theoretical models for the study of g-jitter driven flows and is to construct a ground-based laboratory experimental system and test the system for melt flow measurements. The objective is either completed or being completed. The work on the theoretical part for the first year is completed and the experimental flow measuring facilities are being built and should be finished by the end of the first year.

The theoretical work is concerned about the development of the 2-D theoretical models to analyze the melt flow driven by g-jitter in microgravity and the magnetic field effects on the melt flow. Our model analyses at this stage are based on an analytical model for a simple parallel channel geometry and a numerical model for a 2-D cavity geometry [1-4]. The 2-D cavity geometry is similar to that studied by Alexander et al. [5] who did not consider the magnetic field effects. The analytical model is useful in determining the basic trend and asymptotic behavior of the flow system while the 2-D finite model provides quantitative description of magnetic damping effects. Our analytical model is concerned with both the fluid flow field and temperature field, while the numerical model is capable of predicting the fluid flow field, the thermal field and the concentration profile in a 2-D cavity, which is a simplified version of Bridgman-Stockbarger single crystal growth system. The numerical model is based on the finite element code developed in our laboratory. The code has been tested extensively against the commercial packages including FIDAP and FLOW3D. The numerical modeling results are also compared with the analytical solutions for the simple parallel channel geometry with restricted g-jitter variation and orientations that are intrinsic to the analytical analyses. The comparison is excellent as shown in Figure 1. The numerical model is then applied to study the magnetic damping effects as a function of various conditions including g-jitter variation, orientation and the magnitude and direction of the applied magnetic fields. Some of the results are given in Figure 2. Additional results and detailed numerical computational methodology are presented in a recent publication [3].

The key findings from our work conducted so far may be summarized below. From both analytical calculations and numerical simulations, it is found that the magnetic field, when appropriately applied, will produce adequate damping effects on g-jitter flows in microgravity. The applied magnetic field affects the phase angle of the fluid flow field and a higher magnetic field results in more significant reduction in velocity and reduces the phase angle lag between the oscillating flows and the driving g-jitter. Magnetic damping effects are most effective when the magnetic field is applied in the direction perpendicular to the flow field in the 2-D cavity. The damping effects are more pronounced on low frequency g-jitter driven flows.

Our work from this grant for the first year has resulted in the following publications:

(1) B. Q. Li "G-jitter induced free convection in a transverse magnetic Field," *International Journal of Heat & Mass Transfer*, Vol. 39, No. 14, 1996, pp. 2853-2860.

(2) B. Q. Li "The effect of magnetic fields on low frequency oscillating natural convection," *International Journal of Engineering Science*, Vol. 34, No. 12, 1996, pp. 1369-1383.

(3) B. Pan, B. Q. Li and H. C de Groh, "Finite element analyses of magnetic damping effects on g-jitter induced fluid flow," Spacebound 97 -- *International symposium on microgravity materials science*, Montreal, Canada, May 1997, to appear.

(4) B. Pan, B. Q. Li and H. C de Groh, "Magnetic Damping of G-Jitter Induced Oscillating Natural Convection," for presentation in *Joint Xth European and VIth Russian Symposium on Physical Sciences in Microgravity*, accepted.

The abstracts of these publications are given in Appendix 1. One additional journal paper describing our finite element modeling work is also being prepared at this time.

On the experimental part of our work, we have already finished constructing the calibration unit for calibrating hot film probes for melt flow measurement applications, and started to calibrate the probes for melt flow measurements. We are now in the process of building the experimental unit for melt flow measurements. All these necessary components are acquired or ordered and detailed design has been made. The construction work is underway according to the schedule as detailed in the original proposal. At this point of time, no change in plans as laid out in the original proposal is anticipated.

Our work for the next year will be to follow the work plan laid out in the proposal. We will continue to carry out 2-D simulations and start working on the 3-D numerical model development and 3-D simulations of g-jitter driven flow and magnetic damping effects. The code development has been basically finished and compared with other commercial codes for various applications. We are now in the stage of extending the 2-D model to the 3-D model and simulation results from 3-D model will then be obtained. One primary difficulty associated with 3-D simulations is the adequate computing power. We are currently applying for an account for the use of supercomputer at Pittsburgh Supercomputing Center for the 3-D flow simulations. We will finish constructing the experimental system and will collect melt flow data and compare the measured data with numerical modeling results.

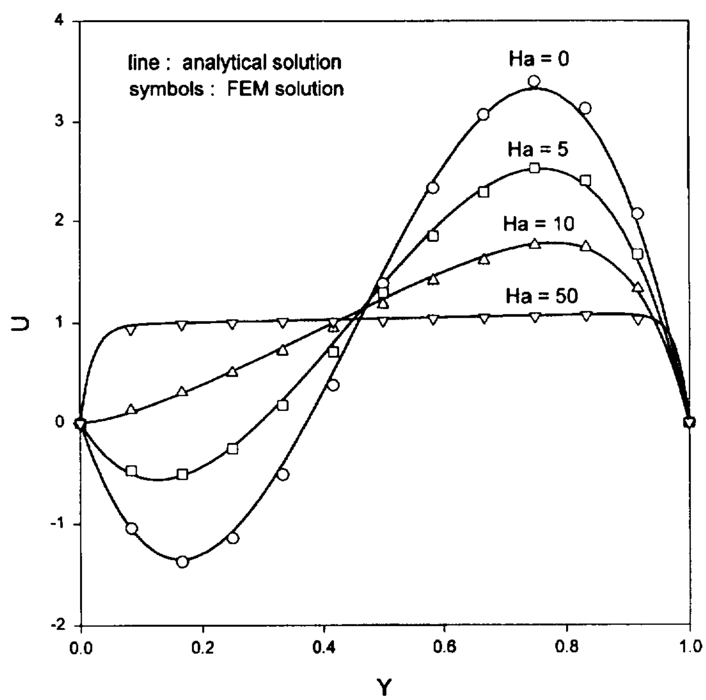
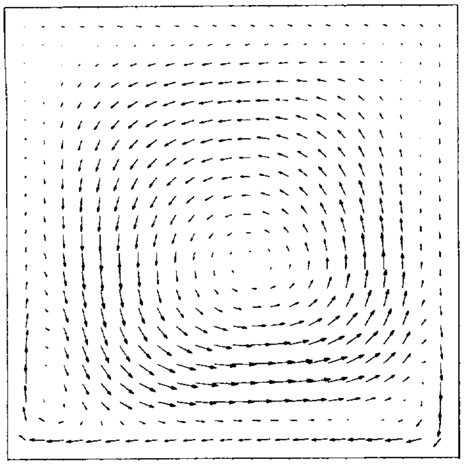
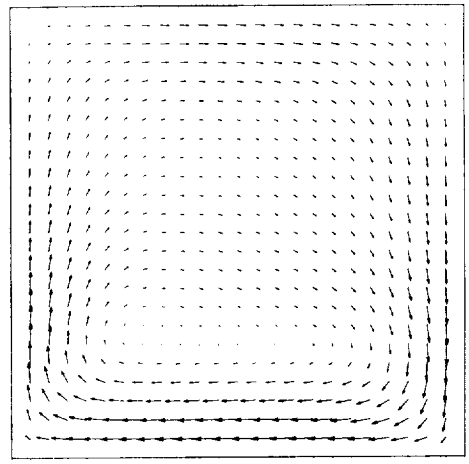


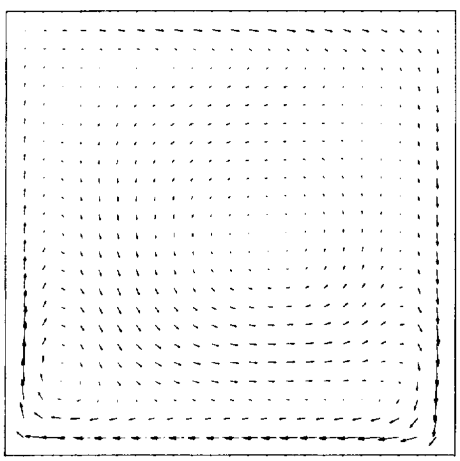
Figure 1. Comparison of numerical and analytical results for magnetic damping of g-jitter driven flow in a parallel plate channel, where y is the direction of the channel width and variables are nondimensionalized.



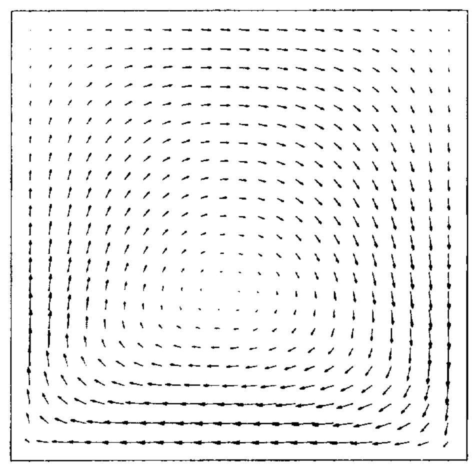
(a) U_{max}=0.120 mm/s, t=6 sec
(without B-field)



(b) U_{max}=0.200 mm/s, t=10 sec
(without B-field)



(c) U_{max}=0.114 mm/s, t=6 sec
(with B-field)



(c) U_{max}=0.188 mm/s, t=10 sec
(with B-field)

Figure 2. The applied magnetic field effect on the g-jitter driven fluid flow in a 2-D cavity, as calculated using the 2-D finite element model (the Hartmann number, Ha=10). The fluid is Ga-doped germanium and parameters for computation are given in abstract of paper 4 on Page 6.

References:

1. B. Q. Li "G-jitter induced free convection in a transverse magnetic field," *International Journal of Heat & Mass Transfer*, Vol. 39, No. 14, 1996, pp. 2853-2860.

2. B. Q. Li "The effect of magnetic fields on low frequency oscillating natural convection," *International Journal of Engineering Science*, Vol. 34, No. 12, 1996, pp. 1369-1383.

3. B. Pan, B. Q. Li and H. C de Groh, "Finite element analyses of magnetic damping effects on g-jitter induced fluid flow," Spacebound 97 -- International symposium on microgravity materials science, Montreal, Canada, May 1997, to appear.

4. B. Pan, B. Q. Li and H. C de Groh, "Magnetic damping of g-jitter induced oscillating natural convection," for presentation in *Joint Xth European and VIth Russian Symposium on Physical Sciences in Microgravity*, accepted.

5. Alexander, J. I. D., Amiroudine, S., Quazzani, J. and Rosengerger, F. (1991). Analyses of low gravity tolerance of Bridgman-Stockbarger crystal growth. Transient and periodic accelerations. *J. Crystal Growth*, Vol. 113, p.21.

APPENDIX 1: ABSTRACTS OF PUBLICATIONS SPONSORED BY THE GRANT

Paper 1: B. Q. Li "G-jitter Induced Free Convection in a Transverse Magnetic Field," *International Journal of Heat & Mass Transfer*, Vol. 39, No. 14, 1996, pp. 2853-2860.

ABSTRACT: This paper reports an analytical analysis of g-jitter induced flows in microgravity under the influence of a transverse magnetic field. The analysis is carried out for a simple system consisting of two parallel plates held at different temperatures. A single component of time harmonic g-jitter is considered. General solutions are obtained for the velocity profile with a combined effect of oscillating g-jitter driving force and induced Lorentz force, the latter resulting from an application of a transverse magnetic field. Various limiting cases are examined based on the general solutions. Detailed calculations are also provided. Results show that the g-jitter frequency, applied magnetic fields and temperature gradients all contribute to affect the convective flow. It is found that the amplitude of the velocity decreases at a rate inversely proportional to the g-jitter frequency and with increase in the applied magnetic field. The induced flow oscillates at the same frequency as the affecting g-jitter, but out of a phase angle. The phase angle is a function of geometry, applied magnetic field, temperature gradient and frequency. While a magnetic field can be applied to suppress oscillating flows associated with g-jitter, it is more effective in damping low frequency flows but only has a moderate damping effect on the flow induced by high frequency g-jitter. The temperature gradient also has a profound effect on the g-jitter induced flow. The oscillating velocity profile evolves from a single wave to a half wave across the channel and the maximum magnitude of the velocity increases as much as a factor of 3 as the wall temperature parameter increases. The wall electric conditions also affect the flows and stronger damping effects occur when the walls are electrically conducting.

Paper 2: B. Q. Li "The Effect of Magnetic Fields on Low Frequency Oscillating Natural Convection," *International Journal of Engineering Science*, Vol. 34, No. 12, 1996, pp. 1369-1383.

ABSTRACT: Oscillating natural convection and its behavior in a transverse magnetic field are described in this paper. The analysis is carried out for a conducting fluid flowing in a parallel plate configuration. The flow is driven by oscillating buoyancy forces originating from g-jitter accelerations associated with microgravity environment. General solution for an oscillating flow as affected by a magnetic field is obtained. Based on the solution, asymptotic analyses are performed to assess the limiting features of the oscillating flow and in particular its response to an applied magnetic field. Detailed calculations are also given. It is found that the behavior of oscillating free convective flows depends on many parameters including the frequency and amplitude of the driving buoyancy forces, the temperature gradient, the applied magnetic field and the electric conditions of the channel walls. In the absence of a magnetic field, the component of the affecting buoyancy forces with the largest ratio of the amplitude over frequency plays a predominant role in driving the oscillatory flow. The flow patterns and velocity magnitude are also affected by temperature gradients. An external magnetic field can be applied to suppress the oscillating flow and also helps to bring the flow to oscillate in phase with the affecting buoyancy forces. The velocity reduction is inversely proportional to the square of the applied magnetic field with conducting walls but directly proportional to the inverse of the magnetic field with insulating walls. Another important characteristic of the magnetically damped oscillating free convection is that unlike the classical Hartmann problem, no thin boundary layer is developed near the solid walls with a high magnetic field and the oscillating flow can be damped completely if a large enough magnetic field is applied.

Paper 3: B. Pan, B. Q. Li and H. C de Groh, "Finite element analyses of magnetic damping effects on g-jitter induced fluid flow," Spacebound 97 -- *International symposium on microgravity materials science*, Montreal, Canada, May 1997, to appear.

ABSTRACT: This paper reports an on-going research on numerical modeling and experimental analyses of magnetic damping effects on g-jitter driven flow in microgravity environment. A finite element model is developed to represent the fluid flow, thermal and mass transport phenomena in a 2-dimensional cavity under g-jitter conditions with and without an imposed magnetic field. The numerical model will be checked by comparing with a published analytical solution for a simple parallel plate channel flow driven by g-jitter under the influence of an imposed magnetic field. The model is then applied to study the effect of both impulse and steady state g-jitter variation on convective flow and on the solute redistribution in a 2-D cavity that bears a direct relevance to crystal growth systems applied in space. Magnetic effects on the fluid flow induced by g-jitter, both impulse and steady state, are also studied using the finite element model. A selection of computed results obtained from the numerical model will be presented.

Paper 4: B. Pan, B. Q. Li and H. C de Groh, "Magnetic Damping of G-Jitter Induced Oscillating Natural Convection," for presentation in *Joint Xth European and Vith Russian Symposium on Physical Sciences in Microgravity*, accepted.

ABSTRACT: Much of the interest in going to space to carry out the melt growth of semiconductors and/or metal crystals originates from the desire to reduce buoyancy driven flow through a significant reduction in gravity. While microgravity environment is helpful in suppressing natural convection, recent space experiments showed that g-jitter or residual accelerations associated with microgravity can cause substantial convective flows in the melt pool, making it difficult to realize diffusion controlled growth as originally intended. Magnetic damping may be applied, in combination with microgravity, to further reduce the g-jitter induced flow, thereby achieving a pure diffusion controlled growth condition.

This presentation describes our investigation on magnetic damping of g-jitter induced oscillating convective flows in melts in microgravity. Both analytical and finite element analyses will be presented. The analytical solution represents a simplified one-dimensional parallel plate model of g-jitter induced flows. Some general behavior of the magnetic field effects on g-jitter driven flow is examined using the analytical solution and some interesting features of the magnetic damping effects will be discussed. It is found that an external magnetic field is able to further reduce the g-jitter induced convection, and the damping effect is more effective on oscillating flows driven by g-jitter components of higher frequency than those of lower frequency. Also, the application of the magnetic field helps to bring the flow to oscillate in phase with the affecting g-jitter driven flows. Furthermore, the Hartmann layer near the solid walls is determined by both the applied magnetic field and the oscillating frequency of g-jitter and is in general thinner for an oscillating flow.

To further study the magnetic damping of g-jitter driven flows, a finite element model has been developed. The model is developed based on the Galerkin finite element solution of the Navier-Stokes equations for fluid flow with applied magnetic damping forces, of the thermal balance equation for energy transport and of the species transport equations for solutal distribution in a melt cavity in microgravity. With this model, more complicated flow conditions can be examined. Figure 1 (see figure 2 in the report, page 3) compares the results of convective flows in a 2-D cavity of Ga-doped germanium melt with and without an applied magnetic field at two different time steps. The cavity has a dimension of 1 cm x 1 cm with the temperatures at the top and bottom fixed at 1331 K and 1231 K, respectively. A composite of g-jitter components with magnitudes (g) of 10^{-2}, 10^{-3}, 10^{-4} and corresponding frequencies (Hz) of 1, 0.01, 0.1 was used and assumed to act in the direction perpendicular to the temperature gradient. A reduction in velocity is apparent with the applied magnetic field. Note also that the application of the magnetic field results in a thin Hartmann layer near the walls. More results obtained from both analytical and finite element models will be presented in the conference.